Status of NASA's Deep Space Optical Communications Technology Demonstration

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

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DSOC Motivation

- **State of the art RF communications continues to provide robust service**
  - Expect performance to eventually level out due to bandwidth constraints**

NASA Technology Roadmap TA5: Communication, Navigation, and Orbital Debris Tracking and Characterization System (May 2015 Draft)

- **Overarching NASA Technology goal is**

  "… seek increased data-rates (10 to 100 times) without increasing mission burden in mass, volume, power and/or spectrum."

- **Optical Communication sub-goal**

  "… provide higher data rate links for near-Earth **and enable more efficient photon-starved links for deep space**

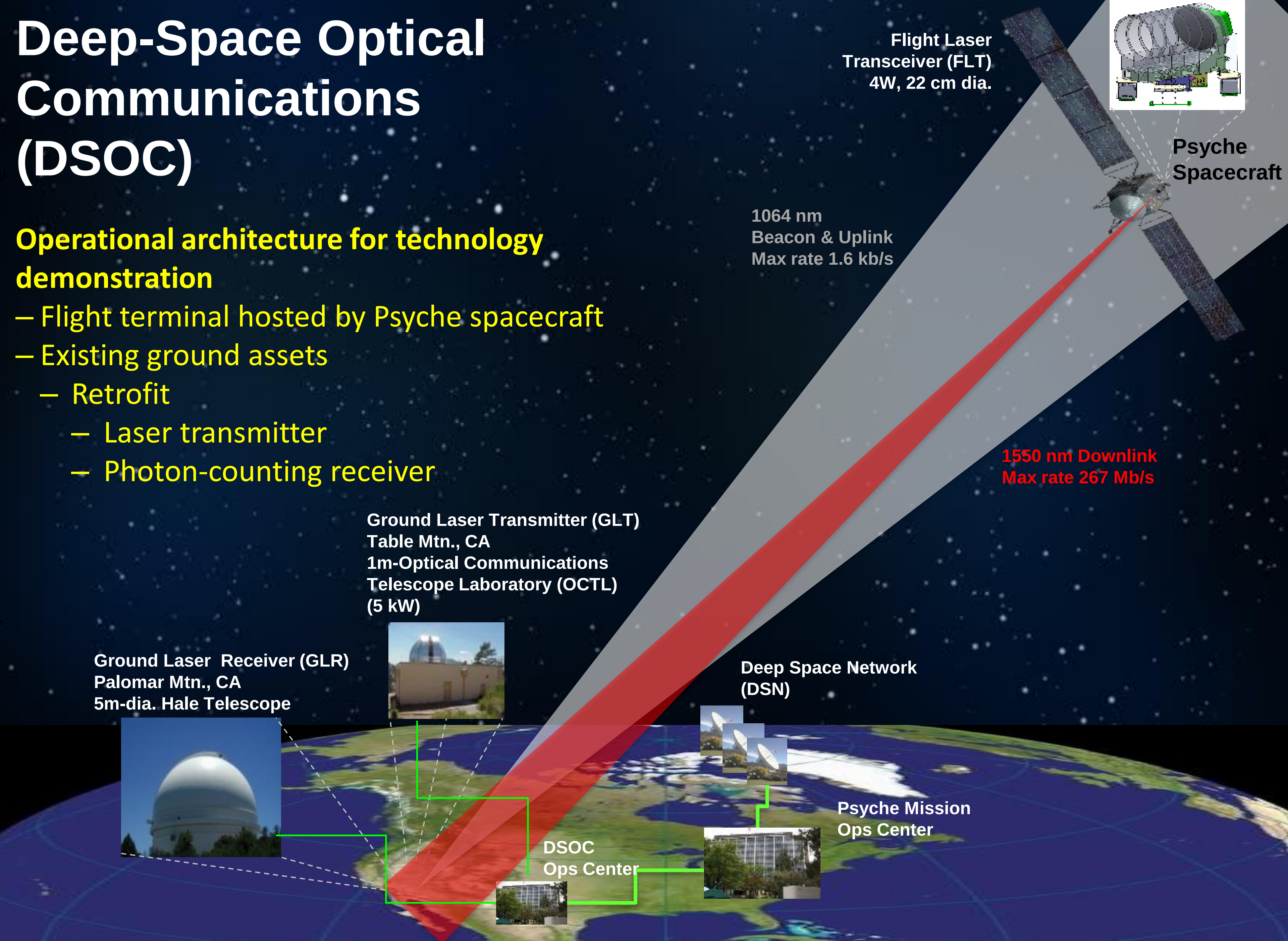
Ongoing development with NASA support

*** Les Deutsch, "DSN Future: A User Perspective," Feb. 20, 2014, DSN 50th Anniversary Symposium*

Deep-Space Optical Communications (DSOC)

Operational architecture for technology demonstration

– Flight terminal hosted by Psyche spacecraft
– Existing ground assets
  – Retrofit
    – Laser transmitter
    – Photon-counting receiver



Tech. Demo Objectives & Approach

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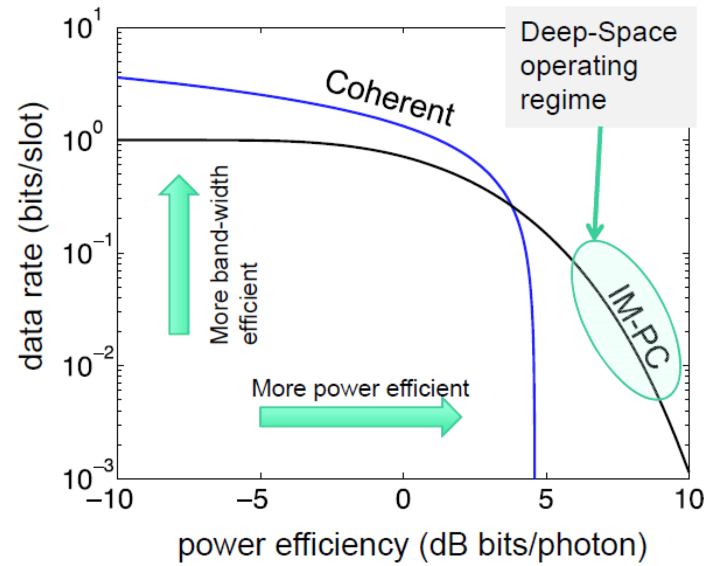
- **Validate deep space optical communications**
  - Link acquisition re-acquisition at both ends of link
  - Tracking of beacon and beacon assisted point-ahead angle implementation'
  - Flight ground signaling compatibility in presence of Doppler and Doppler rates
  - Bi-directional data transfer (unsymmetrical)
  - Performance under diverse link and atmospheric conditions



- **Deep space optical communications involves increased link difficulty**
  - Mbps $\times$ AU^2 targeted by DSOC ranges from 5 -18 compared to
  - 30 dB increase in link difficulty compared to lunar distance
  - Use high photon-efficiency (HPE) emerging CCSDS Optical standard signaling
    - Physical layer
    - Coding and synchronization layer
  - Utilize new technologies for photon-counting and low bandwidth pointing control assisted by spacecraft coarse body pointing

DSOC Tech. Demo Constraints

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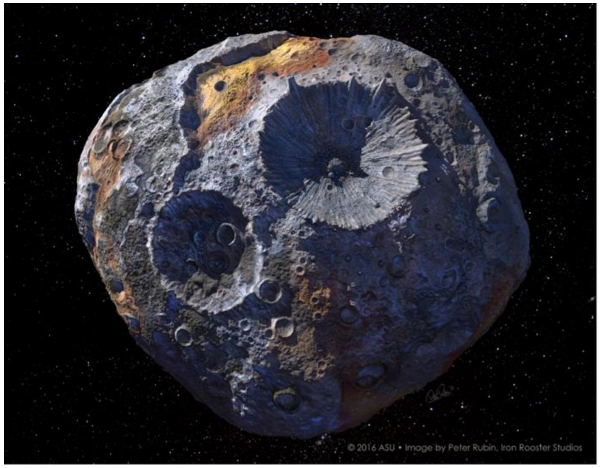
- **NASA/JPL has been pursuing the development of deep space optical communication for decades**
- **Based on readiness through years of incremental technology development NASA has arranged to accommodate a DSOC tech demo hosted by the planned Psyche Mission**
  - Selected by Discovery Program to explore the asteroid Psyche-16
  - Primary science objective is to determine whether Psyche-16 is a core or if it is unmelted material
  - Psyche scheduled for launch in summer of 2022 with a 21-day launch window
    - Schedule constraint
- **DSOC tech. demo constrained by:**
  - Scheduling around Psyche mission activities and ground assets (Palomar)
  - Cloud free line of site at Palomar and OCTL simultaneously
    - Studies indicate an average of about 50% joint availability with seasonal variations
  - Limitations of Palomar telescope to operate in the daytime
  - Psyche trajectory



Artists rendition of Psyche-16

Link Conditions

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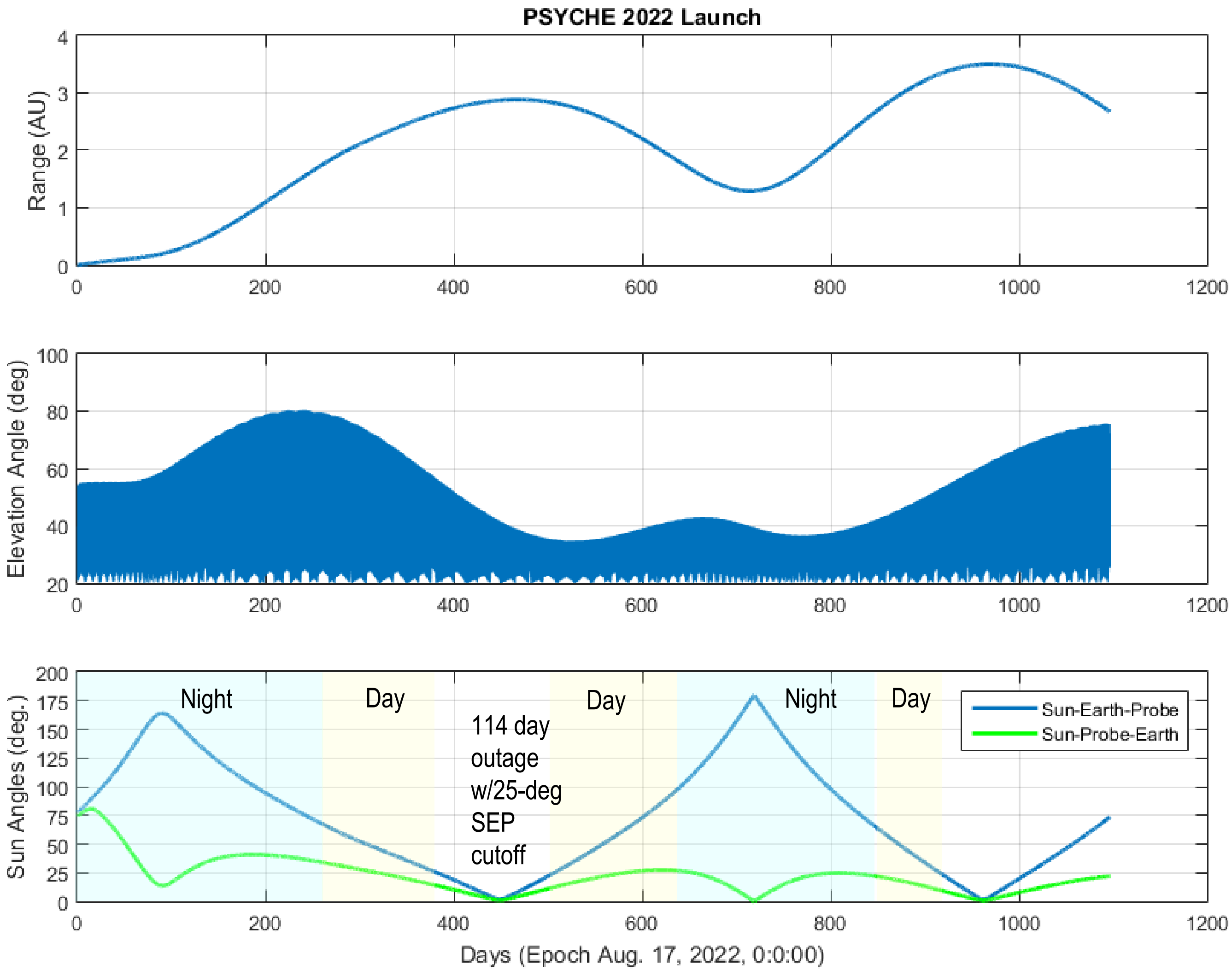
- **Psyche trajectory for observer at Palomar**:
  - Range
  - Air-mass
  - Sun angles
- **“Night” operations for nearly 250 days after launch**
- **“Day” operations restricted to 25° SEP (TBC)**
- **Possible to meet Level 1 requirements within year from launch**
  - Likely requires two contacts per month
  - Frequency of contacts needs further analysis



Link Conditions (cont.)

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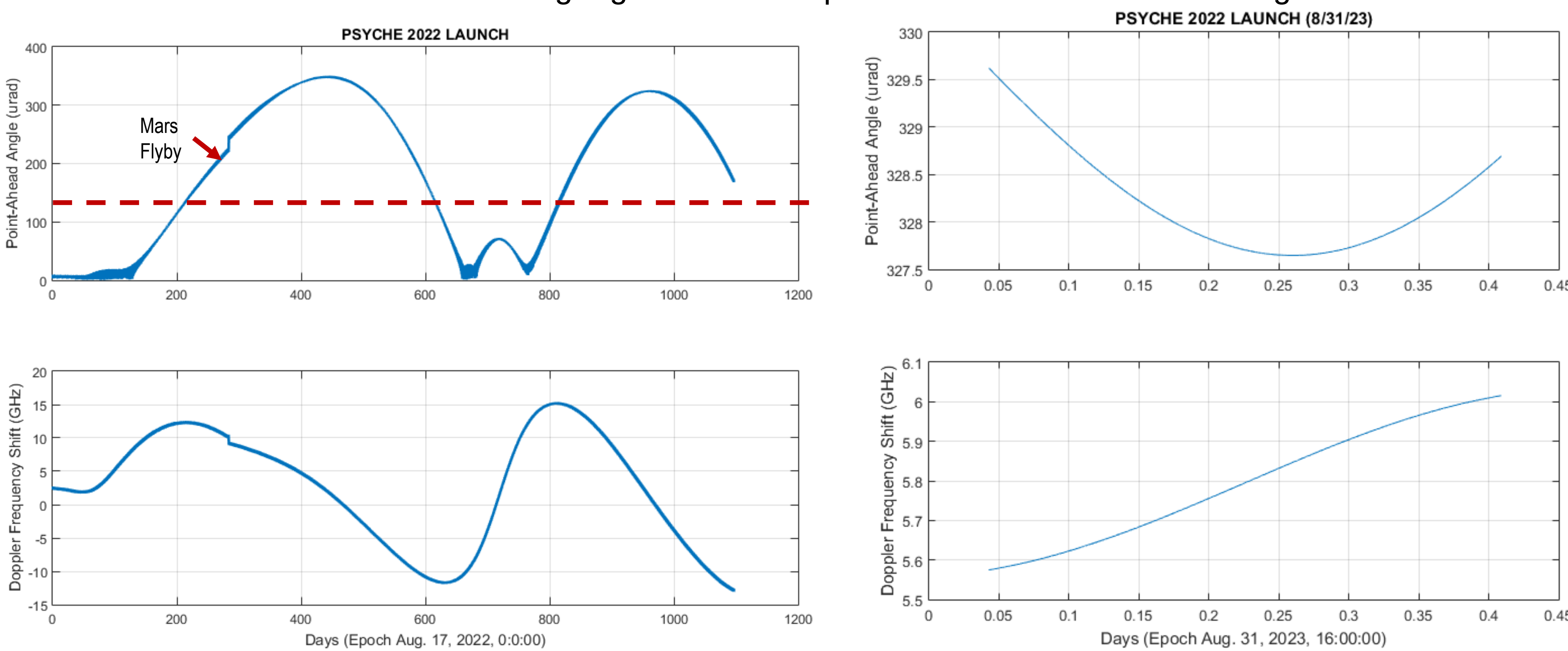
- Doppler shift/rates within optical filter widths and receiver synchronization algorithms
  - Downlink uses narrower filter and would be set based on predicts
  - Uplink filter would accommodate Doppler shifts
- Point ahead angles for downlink exceed FLT camera FOV
  - Factored into design
  - Plan to use calibrated strain gauge sensors on point-ahead mirror when PA angle exceeds FOV



DSOC Concept of Operations

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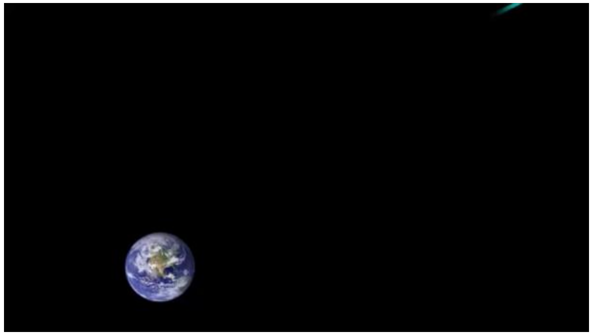
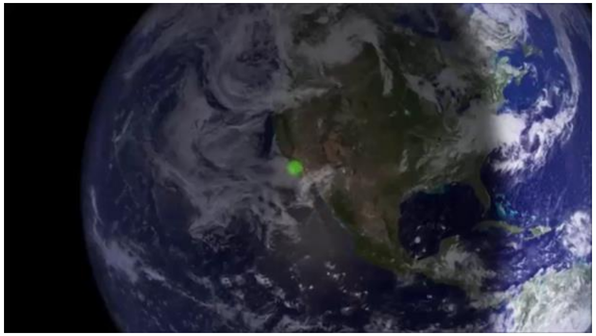
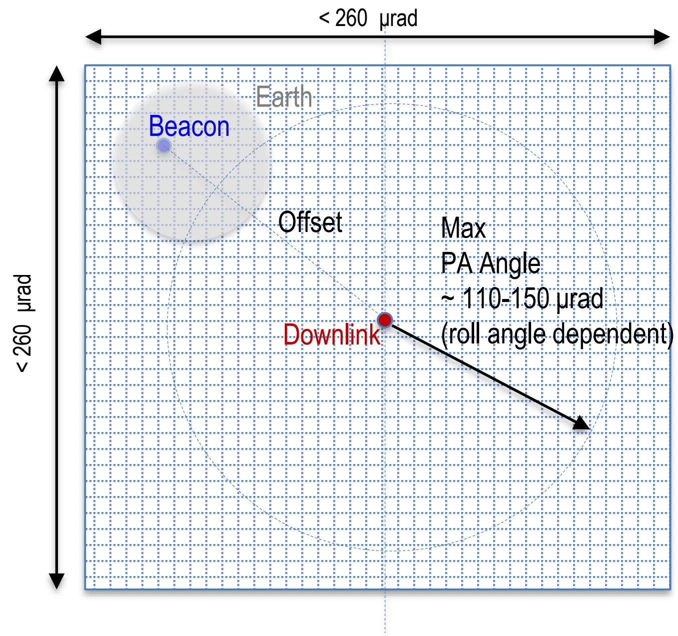
- DSOC tech demo operations concept is under formulation
  - Assumptions
    - Transmit ground laser beacon using predicts while Psyche powers FLT and coarse points to Earth
    - DSOC performs step-stare to search for beacon in s/c pointing uncertainty space
    - FLT stabilizes line-of-sight to Earth with beacon assisted closed-loop control
    - Points downlink to Earth while Ground Receive is pointing to Psyche using predicts
    - Receive and store downlink
  - Telemetry gathered and stored at FLT for post pass transmission to ground
  - Limited “real time” telemetry during pass







DSOC Predicted Downlink Performance

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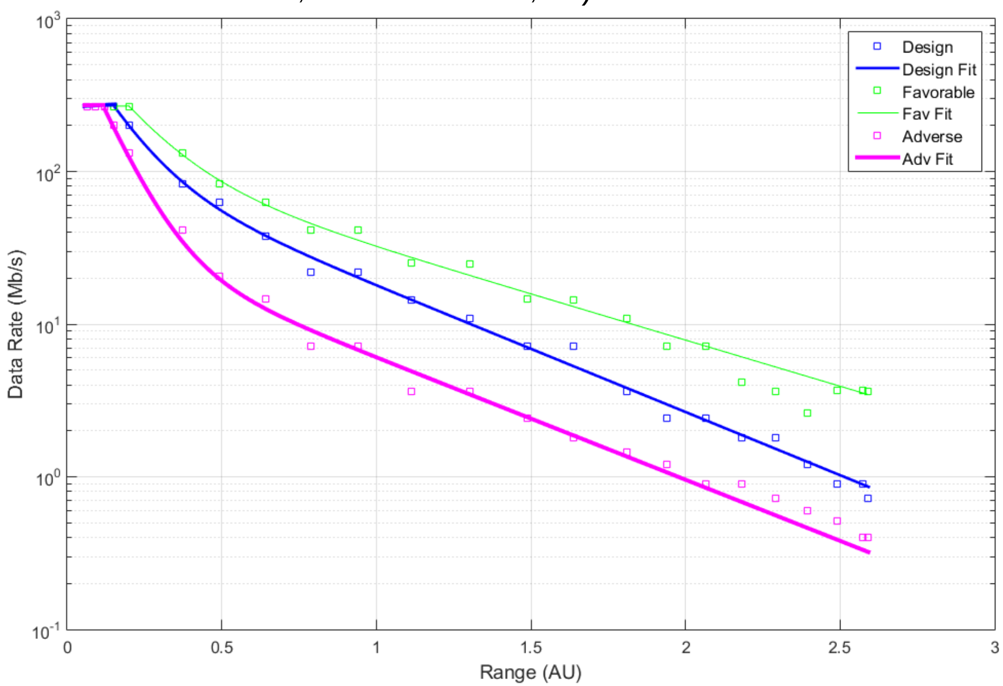
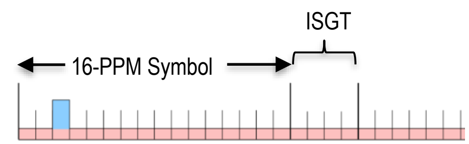
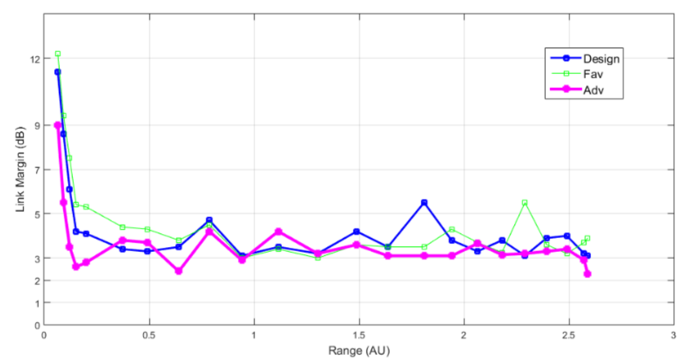
- **Summary of initial downlink analysis**
  - Assumes 4 W average laser power @ 1550 nm transmitted through 22 cm aperture transceiver
  - Received by 5 m diameter ground aperture and detected using photon-counting detector assembly
  - Pulse position modulation (M-ary PPM) orders with M=16, 32, 64, 128 with discrete slot-widths of [0.5, 1,2,4, 8] ns
  - Discrete code rates of 0.33, 0.5 and 0.6667
  - Inter-symbol guard times (ISGT) used to assist temporal synchronization
  - Results show represent fits to data obtained after initial analysis
  - Atmospheric model derived transmission, sky radiance and “seeing” (*models have been authenticated with site statistics gathered at Table Mtn., CA and Goldstone, CA*)







DSOC Predicted Uplink Performance

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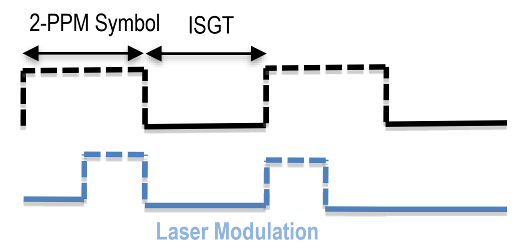
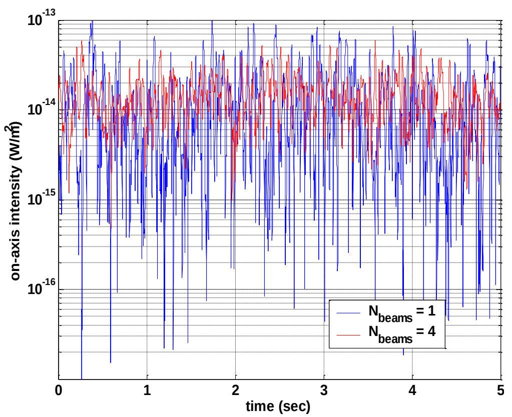
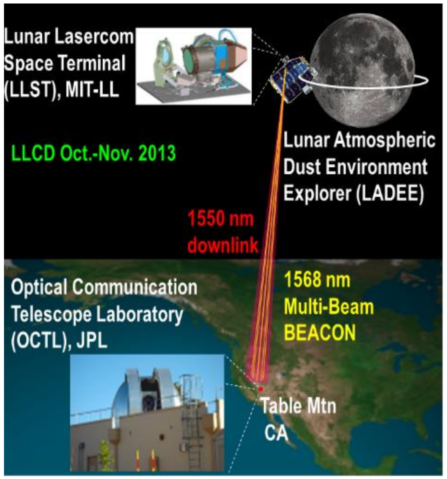
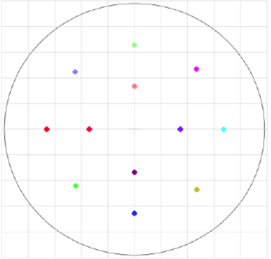
- **Uplink delivers mean irradiance at FLT aperture for acquisition/tracking**
  - 4.5 pW/m^2 irradiance needed for acq./track
  - Modulated beacon allows background subtraction
  - Low-rate (max 1.6 kb/s) uplink data
- **Retrofit multi-beam laser beacon @ 10645 nm to OCTL telescope**
  - Baselining 10 × 500 W total of 5 kW average power
  - Beacon average power supports
    - Uplink data to 1 AU
    - Acq./trk reference to at least 2.6 AU



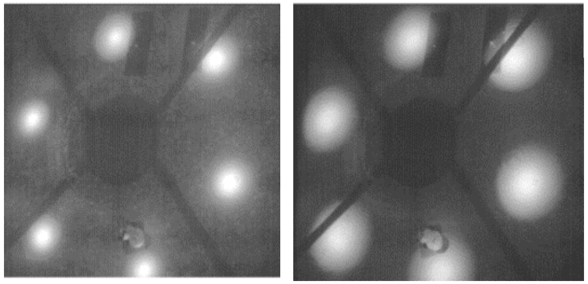


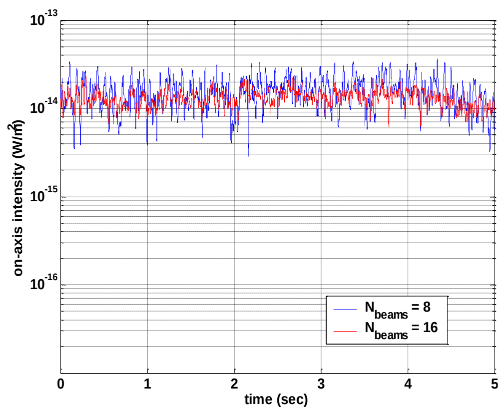


Conceptual beamlet footprint for DSOC



Uplink beamlets on primary used for LLCD





FLIGHT LASER TRANSCEIVER DEVELOPMENT

DSOC Flight Laser Transceiver (FLT)

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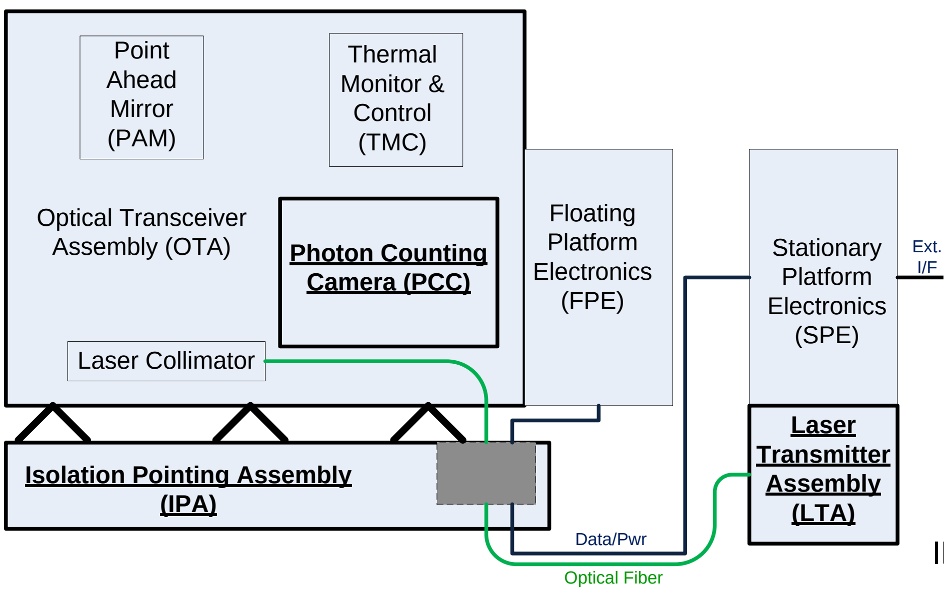
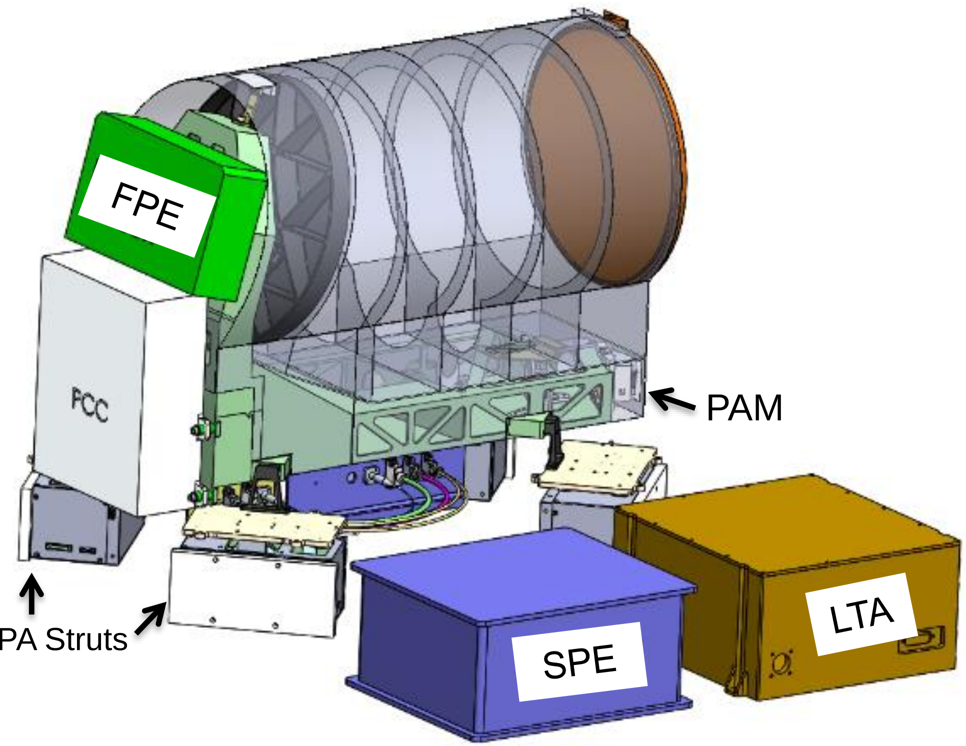
- **The Flight Laser Transceiver (FLT) makes up the flight subsystem**
  - **Silicon carbide (SiC)** Optical Telescope Assembly (OTA) receives beacon and transmits downlink
  - **Photon Counting Camera (PCC)** detects “dim” 1064 nm laser beacon transmitted from Earth
  - **Isolation Pointing Assembly (IPA)** “floats” OTA to stabilize and steer OTA line-of-sight
  - **Laser Transmitter Assembly (LTA)** delivers high peak power pulse train modulated by downlink data
  - **Electronics** – firmware/software platforms, power and clock distribution for “floating” and stationary parts, power and data interface to spacecraft





Prototype FLT Assemblies

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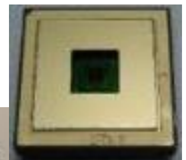
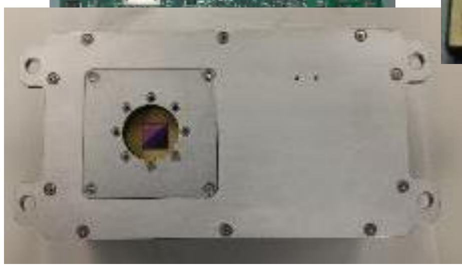
Power Supply Unit
216 × 209 × 81 mm

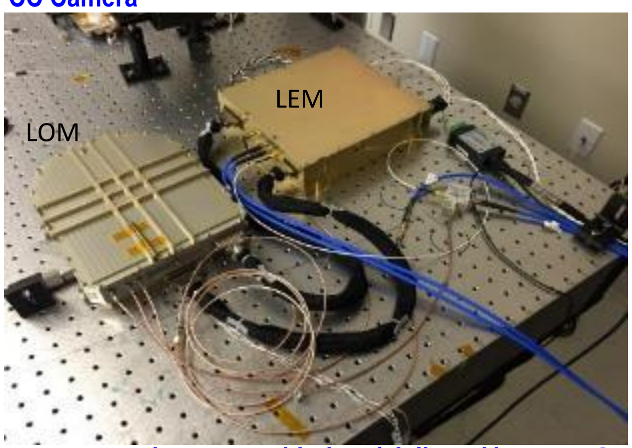
PCB Board



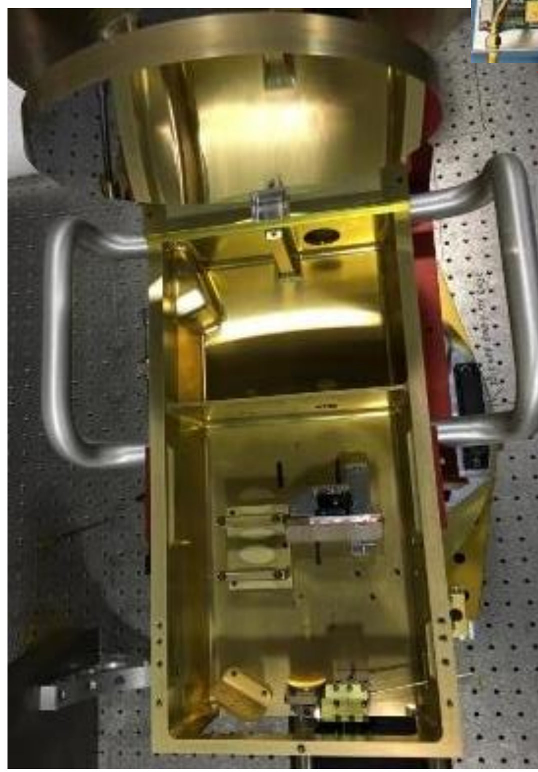


Sensor Package

PCC Camera



Laser Transmitter Assembly (LTA) (Fibertek) : Laser Optical Module (LOM) and Laser Electrical Module (LEM)



Optical Transceiver Assembly

GPP Board in Test Chassis

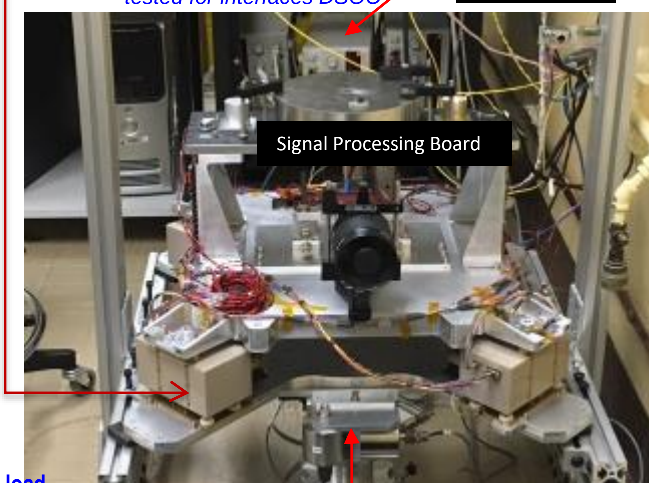
DSOC GPP
SN 004

Interface Board
SN 001 (test only)

Slot for SPB
(when it arrives)

Single strut being tested for interfaces DSOC

Spring and Music Wire Suspension



Disturbance Emulator

IPA Assembly with "dummy" load laboratory characterization

Flight Photon Counting Camera Signal Detection

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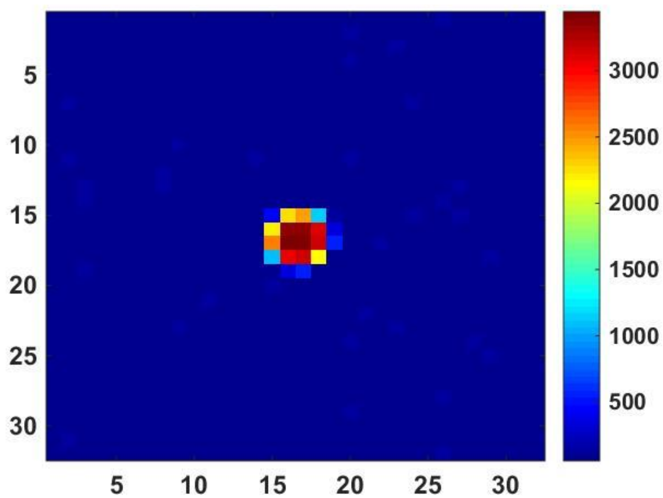
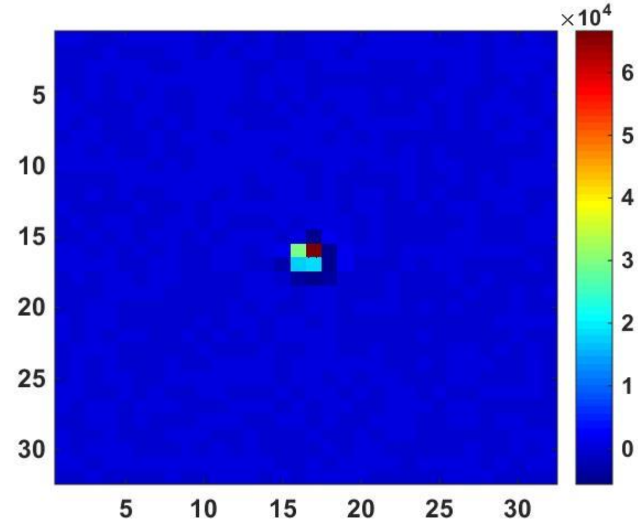
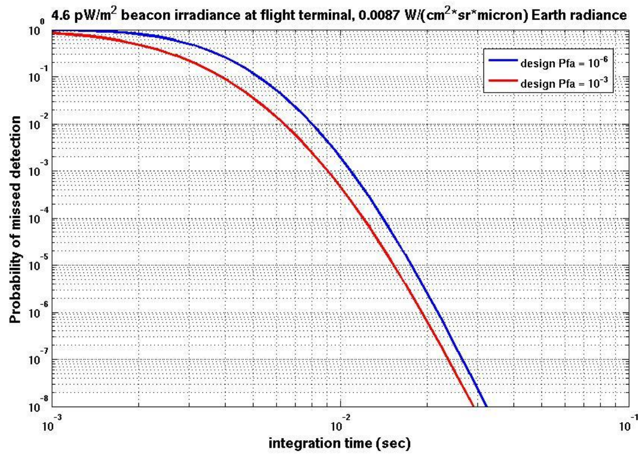




Probability of missed detection



- **Pixel modified square-law statistics are used to distinguish modulated signal from background**
- **Statistic from maximum pixel is compared to threshold to detect signal**
- **For Mars far-range case, statistic integration time of 20 - 40 msec is sufficient to achieve 10^{-6} probability of missed detection**
- **In practice, platform stability will limit integration time**

PCC Performance Results

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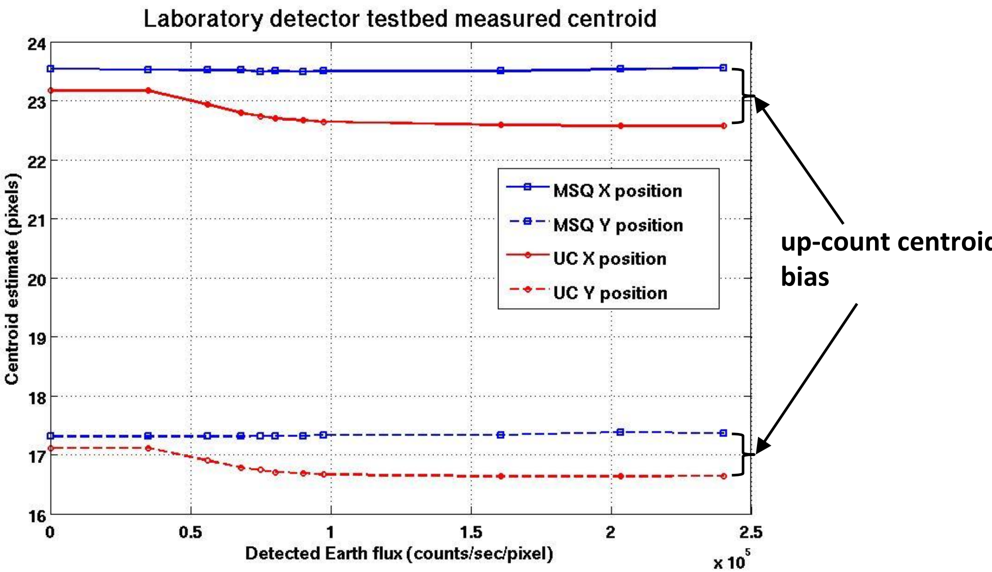

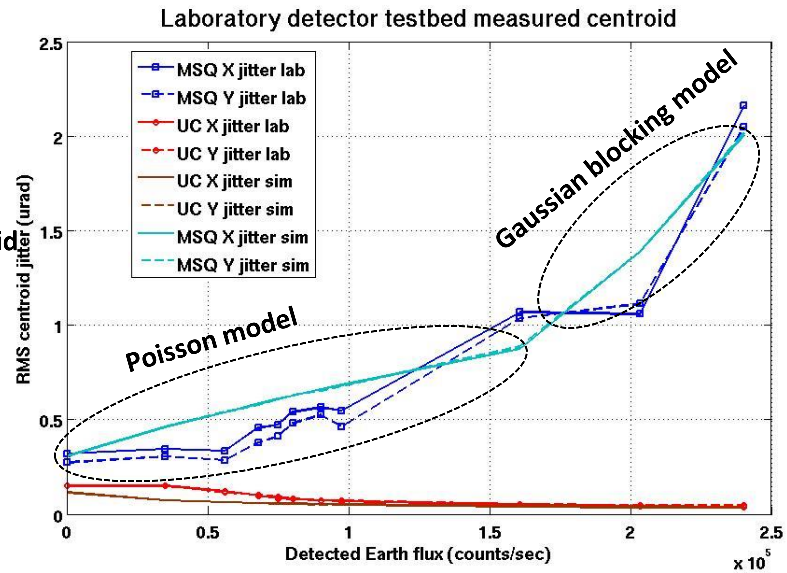

- Uplink UC centroid changes as Earth flux increases, MSQ centroid does not
- MSQ centroid jitter increases with increasing Earth flux
  - At <1.5e5 Earth counts/sec/pixel, per axis jitter < 1 µrad
- Earth-beacon centroid difference ~ 1 pixel in X, ~0.75 pixel in Y (8 µrad, 6 µrad)
- Earth flux per pixel for Mars 2.7 AU ~1.6e5 counts/sec/pixel (assuming 1 nm filter, 3 dB optical losses, 40% DE, irradiance of 0.0087 W/m^2/sr/µm)
- Measured values track simulation results using Gaussian blocking model
- Downlink jitter < 0.16 µrad per axis
- Additional results with better calibrated measurements expected in next few months

LTA Performance Results

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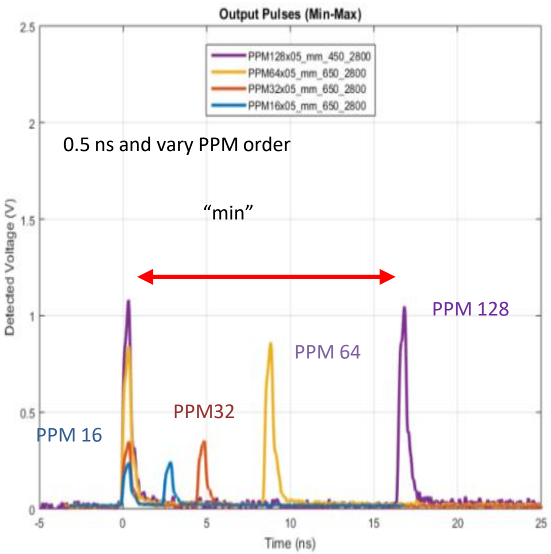
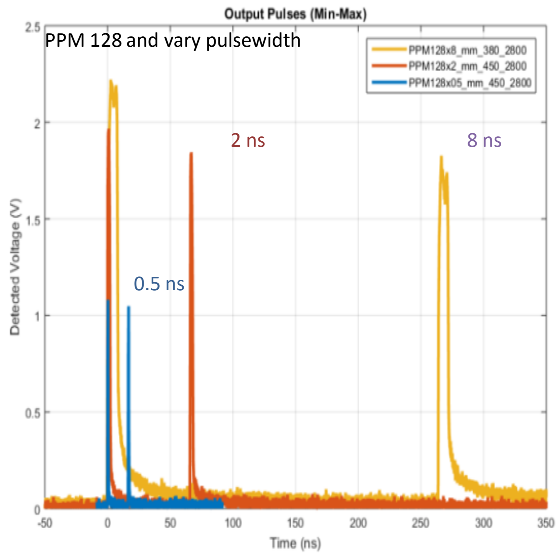
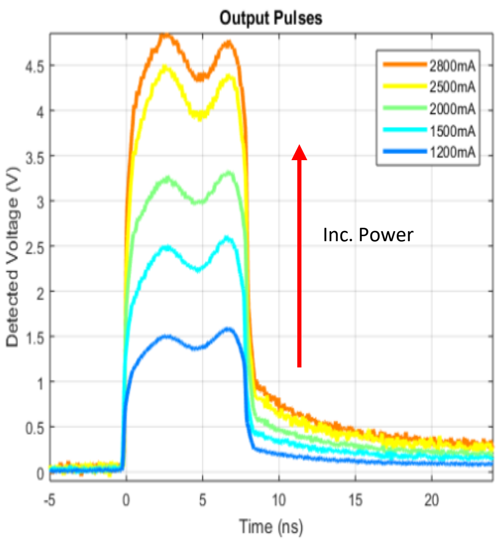
- **LTA prototype built and tested in preparation for flight**
  - Demonstrated performance and select environmental requirements met
  - Maintaining high temporal ER critical over all PPM orders and pulse formats

Pulse format

- PPM 16-128, 25% Guard time, 0.5 – 8 ns with min/max test pattern, ~4W







DSOC FLT Development Status

- **Verified**
  - Laser performance and TVAC, vibe, radiation testing and analysis
  - Photon-counting camera performance in laboratory
    - Centroid estimation algorithms with background subtraction in presence of Earth radiance noise
    - Uplink data demodualtion
  - Isolation pointing strut performance in laboratory with gravity off-load
  - Optical Transceiver Assembly performance with aluminum assembly; also verified SiC mirror separately
  - End-to-end downlink testing at a few operating points (ongoing activity)

- **Completed System Requirements/Mission Definition review on Nov. 1-2, 2017**

- **Work to go**
  - Assemble functional prototype Flight Laser Transceiver (FLT) in laboratory testbed
    - Test acquisition, tracking and pointing using gravity off-load and ground support equipment
    - Perform end-to-end information testing prior to PDR
  - Complete preliminary design and build of FLT assemblies
  - Procure and develop EMs and Flight hardware for the FLT
  - Develop ICD with Psyche Mission and understand accommodation
    - Initiated
  - Integrate and test FLT (performance and environmental)
  - Verify flight – ground signaling compatibility with flight hardware

GROUND DEVELOPMENT

DSOC Ground Subsystem

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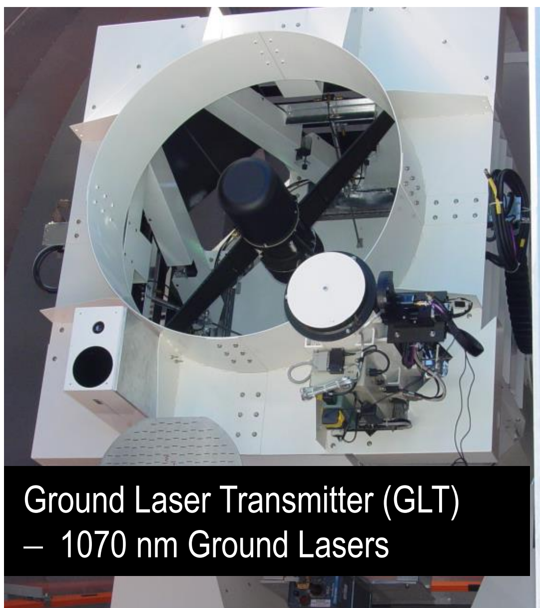
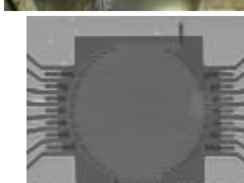
- **DSOC technology demonstration would utilize**
  - Ground Laser Transmitter at OCTL telescope near Wrightwood, CA
    - Retrofit high power (5 kW) laser transmitter
  - Ground Laser Receiver at Hale telescope at Palomar Mountain, CA
    - Retrofit photon-counting detector and signal processing electronics
  - Mission ops center for coordinating ops (not shown)



Ground Laser Transmitter (GLT)
– 1070 nm Ground Lasers

Optical Communication Telescope Laboratory
(OCTL) 1m aperture
Az/El Drive

Hale Telescope
5 m aperture
Palomar Observatory
RA/DEC Drive



Ground Laser Receiver(GLR)
– Photon-counting ground detectors
– 50% Eff. WSi nanowire arrays

DSOC Ground Development Status

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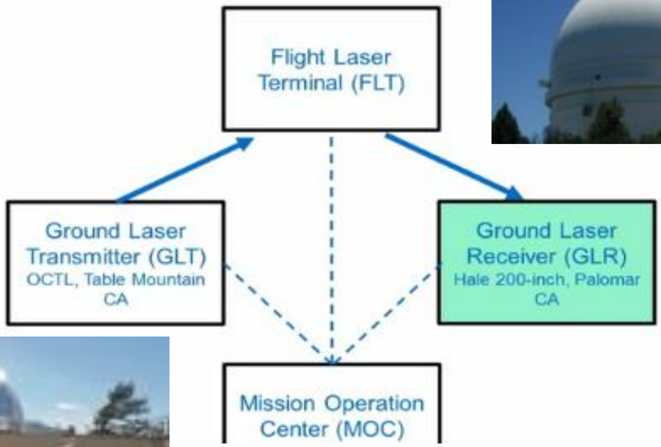
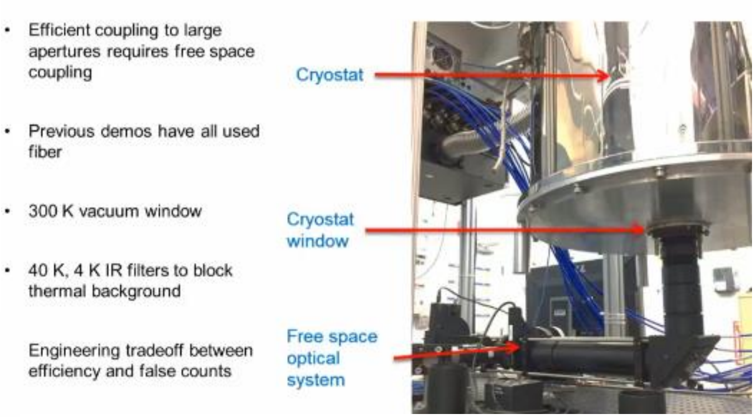
- **Initiated discussions with Caltech Optical Observatories (COO) for the use of Hale telescope at Palomar Mountain**
  - Trade location of DSOC detector at Coudé versus Cassegrain focus
  - Analyze and test impact of telescope use in the daytime (insolation and thermal effects causing "seeing" for nighttime observers
  - COO staff would support this work after August 2017
- **Uplink laser selection for retrofitting to OCTL telescope for ground transmitter**
  - Plan to modulate pumps on high power optical amplifier to achieve 500 W average power 2 kW peak power lasers
  - Packaging of lasers for DSOC is work to go

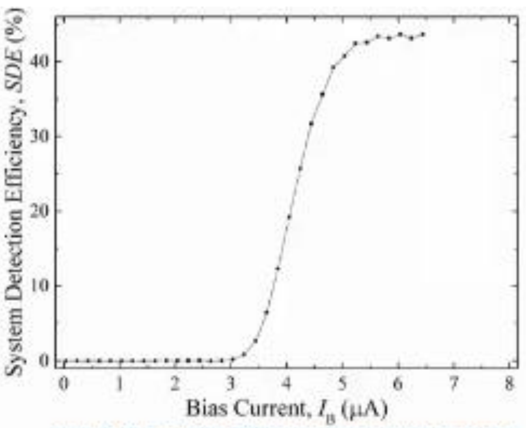


DSOC Ground Detector Development

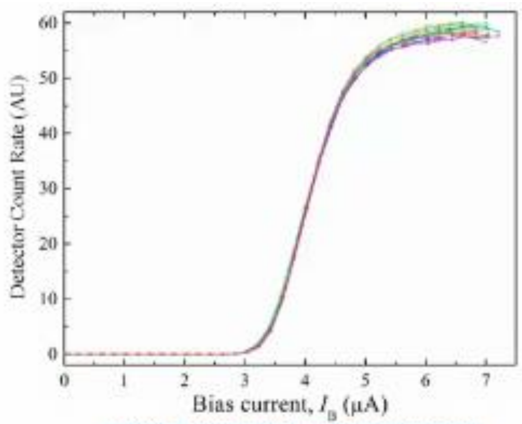
- **Detector fabrication and characterization is ongoing**
  - Fabricated 64-wire tungsten silicide (WSi) superconducting nanowire single photon (SNSPD) detector array
  - Verified characteristics of 320 μm diameter detector (optical micrograph and packaged SNSPD shown below)
  - Detector has been characterized and shown to meet all required specifications
  - Preparing to support end-to-end link tests in laboratory
    - Includes interface to backend signal processing electronics

  - Detector signal conditioned at 40K stage
  - Routed out of cryostat to 64-channel comparator
  - Initiating end-to-end information testing

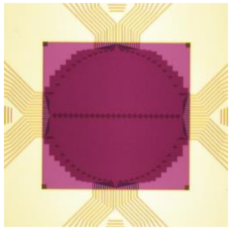


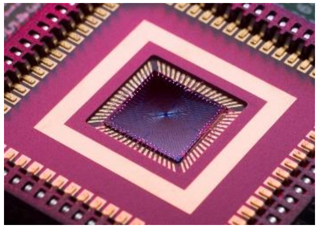


Sum of 16 detection efficiency curves in one quadrant



Individual count rate curves superimposed


Optical microscope image JPL fabricated array.


Packaged SNSPD Array

DSOC Ground Development Status

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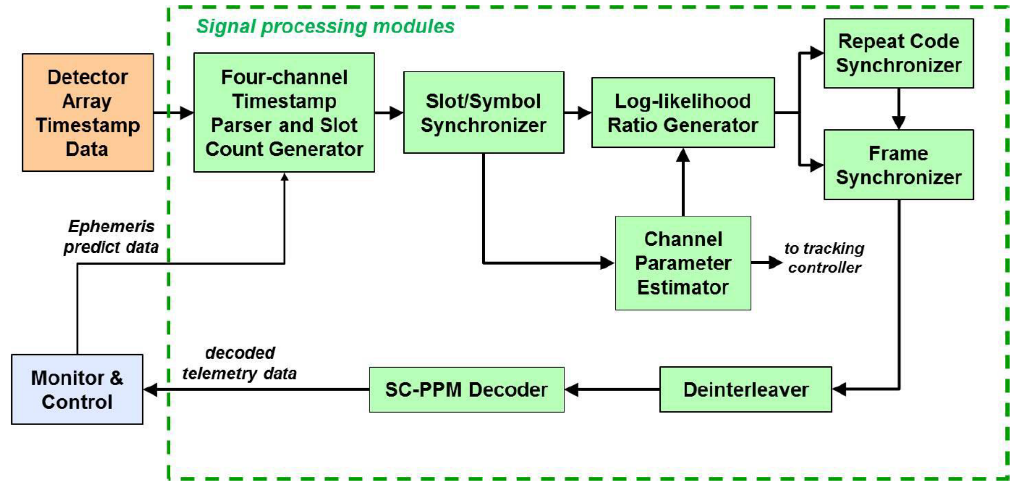
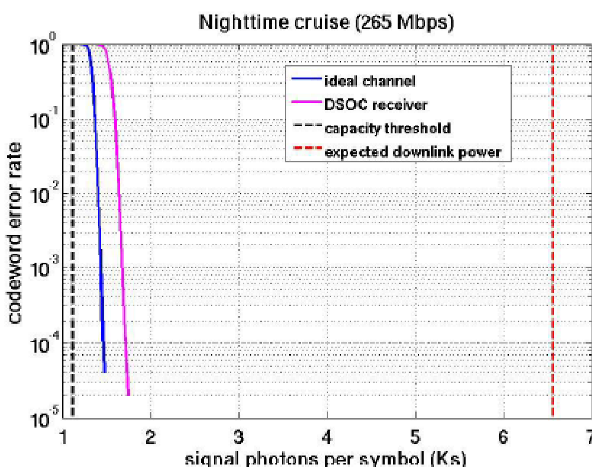
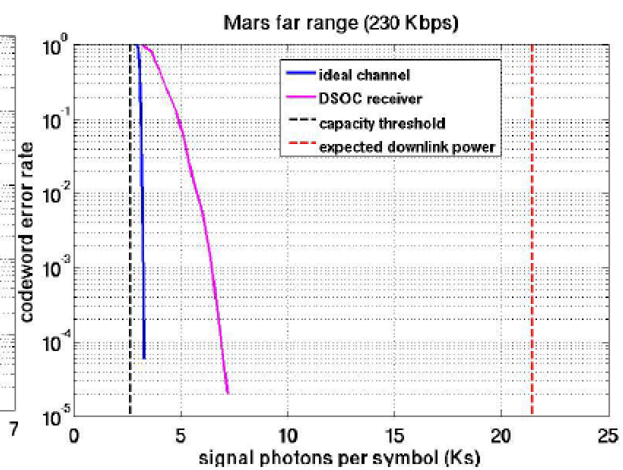
- **Signal processing functions**
  - Synchronize received data to DSOC symbol frames
    - Compensate clock phase and frequency dynamics
    - Strip off inter-symbol guard time slots
  - Estimate signal and background parameters and form log-likelihood ratios
    - Estimate codeword frame boundaries
    - Remove frame alignment sequences
    - De-interleave sub-channel symbols
    - Decode data and return information bits
  - Functions are in various stages of verification through simulation
    - High fidelity simulations (results shown)
    - Verified few operating points in laboratory
    - Rigorous calibration and repeatability pending



Ground Receiver Signal Processing Functional Architecture





Summary

- **Preparing for NASA's first technology demonstration of optical communications from deep space**
  - Pre-cursor to enabling human exploration and enhancing high-resolution science
  - Developing Flight and Ground system to support demonstration

- **DSOC Project privileged to be hosted by Psyche**
  - Provides excellent operational opportunities that are needed for learning how to provide future optical services for NASA missions

- **Understand and managing risks involved with DSOC technology demonstration**

- **Team is excited with this great opportunity**

BACKUP

- **Notional encounter with 16 Psyche**